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ON THE STATISTICAL ANALYSIS AND PROBABILISTIC MODELING OF SHIP MANEUVERING RESULTS FOR WATERWAY DESIGN

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ABSTRACT

This paper presents a new approach to estimate the probabilities of ship accident (collision or grounding) on the basis of ship maneuvering results. Assuming that trajectories of ship track or swept path are considered as the response ensemble of either a stationary or non-stationary random processes, the study then concentrates on estimating the response characteristics by analyzing of their power spectrum density. Finally, the extreme statistics of a ship exceeding the channel limits are determined on the basis of this information. In that way, it subsequently becomes possible to study channel width and channel depth in an integrated manner. A real probabilistic model of ship grounding risk for the whole channel has therefore been established. Numerical examples have been given and the proposed approach has been quantitatively evaluated.

KEYWORDS

Stationary and non-stationary random processes, response ensemble, ship grounding, ship handling simulator, distributions, spectral bandwidth.

INTRODUCTION

Maritime simulation is a reliable and indispensable tool in the assessment of navigational safety of a ship in conjunction with harbors and fairways. The main application focuses essentially on channel design to indicate the ship maneuverability and possible accident occurrence in relation to the human behavior and environmental conditions. From the view point of port engineering, the analysis of the risk of ship accident in each zone of the approach channel on the basis of ship track and swept path is extremely interesting.

The most common analysis methods are those that consider the different channel passage sections to be independent from each other. The analysis thus concentrates on defining the individual starboard and port side distribution functions. The probability of collision or grounding in each of the sections can then be computed by defining the lateral limits exceeding the navigable zone in the Gaussian distributions [2, 4] and [8]. The essential limitation of these methods lies in the fact that there is interdependency between transits in subsequent cross-sections of a channel. The analysis of the separate cross sections can only give separate estimates of the probability of exceeding the channel border in each particular cross section, it can never indicate for the channel as whole [12]. A relatively simple way of determining the risk level of the entire channel is by dividing the channel into a few homogeneous parts then determining the probability of the channel border being exceeded for each part. The length of an independent part relates to a half wavelength of the ship track in the channel, which was estimated [10] by several ship lengths. Again, the critical point resides in the fact that the estimated wavelength of the ship track was defined simply by using judgment and expert rating.

The other method with a different focus was demonstrated by A. Burger [13] taking the interdependence of successive passage sections into account, then either using a linear regression model or Markov chains to determine the interdependency of transits in subsequent cross sections. However, this methodology still needs considerable effort to develop and it is also very costly because it requires a large number of real time simulations [8]. For this reason, this method has not been applied in practical engineering yet.

The purpose of this paper is thus to develop a new approach to this problem; a real probabilistic model of the ship grounding for design of waterways is therefore established.

METHODOLOGIES

Stationary process of ship - pilot behavior

The balance between the competence required by navigational environment and the competence that a mariner can attain for safe ship operations should be maintained [5]. To ensure that the required navigational safety is achieved, the mariner must keep the ship stable so that the fluctuations during the ship maneuvering process are minimized to maintain the track as close as possible to the desired track throughout transit. The magnitude of these fluctuations varies depending, of course, not only on the different environmental conditions but also on the different competencies of mariners and even randomly changing for one mariner with different tests in the same condition. However, the fluctuations for a certain maneuvering condition and one mariner will become "stable" or "stationary" after he has taken several tests; in other words, "non-stationary" or "unstable" process of ship maneuver should be avoided to facilitate the navigational safety. It is therefore possible that the ship response (track, swept path, course, etc.) can be viewed as the output signals of random stationary process and, as indicated above, as having the Gaussian distributions.

The above statement has been verified using the so-called "*Reserve Arrangement Test*" technique [13] based on the data from many real time simulations [2, 6].

Properties of the Gaussian stationary random process

Assume that a real time simulation is set up for a part of the channel with the length L (m), a mariner completes the trail tests in the period T (sec), and $x_i(t)$ is the sample record (sample function) of the ship which is the ship position recorded at predetermined time interval, Δt (*sec*), during trial *i-th*. Let us assume that the ship rarely exceeds the channel border that successive up-crossings of a specified level are independent and can therefore be modeled as the Poisson process. Under these assumptions probability $P(b,T)$ that the response ensemble $\{x(t)\}$ (the symbol {} denotes an ensemble with the number of the sample records is n_s, we omitted n_s to simplify the notation) will cross at level $x=b$ at least once during a period T given by [14]

$$P(b,T) = 1 - \exp(-v_b T), \text{ in which } v_b = \frac{1}{2\pi}\sqrt{\frac{m_{2x}}{m_{ox}}}\exp\left\{-\frac{1}{2}\left[\frac{(b-\bar{\mu}_x)^2}{m_{ox}}\right]\right\} \quad (1)$$

where v_b is the mean rate of crossing with level b (b is considered as a half of the channel width); $\bar{\mu}_x$ is the ensemble mean value of $\{x(t)\}$; m_{ox} and m_{2x} represent respectively zero and second moments of the ensemble $\{x(t)\}$, which can be determined by the following equations:

$$m_{ox} = \int_{-\infty}^{\infty} \bar{S}_{xx}(\varpi)d\varpi, \text{ and } m_{2x} = \int_{-\infty}^{\infty} \varpi^2 \bar{S}_{xx}(\varpi)d\varpi \quad (2)$$

Where $\overline{S}_{xx}(\varpi)$ is the power spectral density *(PSD)* which describes the distribution of the mean-square value of the ensemble $\{x(t)\}$ over the frequency domain. Based upon the ensemble $\{x(t)\}$, $\overline{S}_{xx}(\varpi)$ can be quickly determined by digital computer using the fast Fourier transform algorithm [13].

Record length requirement

One of the most important features to this approach is to determine the total record length requirement, T_r(sec), of the response ensemble (i.e., the minimum total number of observations, N, in the ensemble) to obtain a predetermined degree of accuracy of the power spectral estimate. It is somewhat similar to the required number of trails n_s per environmental condition, generally between 8 and 15 [8] in the other methods, the relationship between them can be clearly expressed by

$$N = \frac{T_r}{\Delta t} = \frac{T}{\Delta t} n_s \tag{3}$$

In practice, to measure the precision of the spectral estimate, its normalized random mean square error (*rms*) is widely used. The minimum total number of observations required for a specified *rms* error, ε, can be determined by using following equation [11]

$$\varepsilon^2 = \frac{3.5044}{\left(NB_h\right)^{5/4}} \tag{4}$$

Where B_h is the spectral bandwidth (*SB*), it is measured [11] as the distance between the half-power points ω_1, ω_2 ($\omega_1<\omega_0<\omega_2$; ω_0 is the peak frequency) which are defined by $S_{xx}(\omega_1)= S_{xx}(\omega_2)= 0.5S_{xx}(\omega_0)$. Thus, $B_h= \omega_1\text{-}\omega_2$. In case the *PSD* has a single peak at ω_0, B_h is thus approximated to ω_2. Equation (4) implies that for a prescribed degree of the precision, N can be estimated as a function of the spectral bandwidth B_h. Unfortunately, this is not always possible since B_h is usually unknown parameter prior to data collection. Certain assumptions based upon prior knowledge of the spectral estimates and expert's judgments are therefore required.

REAL TIME SIMULATIONS

Real time simulations carried out at the Southern entrance channel to Ennore Coal Port, India [6] have been used for the analysis and verification of the foregoing approach. The modeled channel with a length of 6*km* is aligned 345^o north. The simulations were executed with the bulk carrier 65000*DWT* by four local pilots. A total of 37 trials with various environmental conditions were performed, in which 8 succeeded swept path tracks of the extreme conditions from *km*+1.000 to *km*+6.000 were taken for this study; for each having N=900 data values recorded at time interval Δt =1*s* thus making the total time period of a transit T= 900*s*. Since the procedures of calculation on the starboard side are the same as those on the port side, only the latter is considered in the following. An example of a sample record of the swept path is shown in Figure 1.

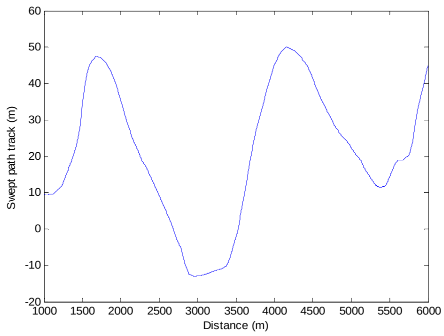

Figure 1: A sample record of ship track (with additional post-processing)

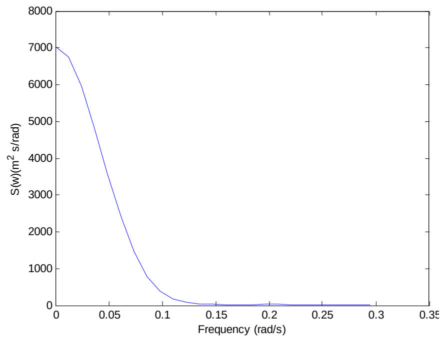

Figure 2: Power spectrum of the response ensemble

(Trial condition: wind 7*Bft*, South-East; wave H_s=2*m*, South-East; and current velocity 0.6*m/s* South-North)

Normalized rms error of the power spectral estimate

Data of the swept paths from 8 trials (i.e., 8 sample records) are considered as a response ensemble $\{x(t)\}$. As revealed in the previous section, before the normalized *rms* error can be evaluated, the spectral bandwidth has to be defined. First, using the ensemble $\{x(t)\}$, determine an estimate of $\bar{S}_{xx}(\varpi)$, the result is as shown in Figure 2. Then we try to estimate B_h based on the estimated bandwidth $\bar{S}_{xx}(\varpi)$. As the definition of B_h, the value of B_h may be derived from Figure 2 about 0.04. Hence, for $N=Tn_s$=7200 and from Equation (4), ε^2 will be 0.0378. Clearly, the precision of this approach depends only on the number of the observations, whereas the number of trails must be required large enough in the other methods.

Probabilities of ship grounding

When the estimate of $\bar{S}_{xx}(\varpi)$ is available; from Equations (1) and (2), the probabilities of ship grounding can be quickly determined for a certain half of channel width. These probability results for various half channel widths are plotted in the upper curve of Figure 3.

As discussed above, if the entire channel can be viewed as consisting of a number of homogeneous parts, which relate to a half wavelength of the ship swept path, this approach can provide an expression to estimate the probability of ship grounding as

$$P(b,T)=\left(\frac{L}{T}\right)\left(\frac{T_c}{2}\right)\int_b^{\infty} f(x)\mathrm{d}x,\ \text{here } T_c = 2\pi\sqrt{\frac{m_{ox}}{m_{2x}}} \tag{5}$$

where *f(x)* is the density function of ship position (swept path), which can, as indicated, be well described by the Gaussian distribution; T_c is the mean zero-crossing period of the wavelength.

The results for various half channel widths are also plotted in the lower curve of Figure 3. It can be seen from this figure that these results become almost the same as those computed by the proposed approach when *b* is greater that 110*m*. The values of *b* within this area are very close to a designed point since an acceptable probability of ship grounding is quite low, let's say about 3.10^{-5} [10].

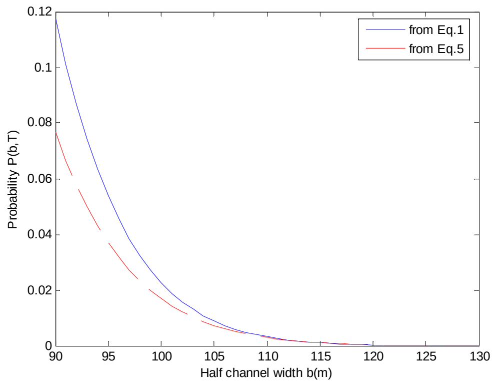

Figure 3: Probabilities of ship excursion vs. half channel width

FULL PROBABILISTIC EQUATION

Supposing that a ship is grounded when escaping from the channel border is not realistic for the case of a flooded channel or a dredged bank. This is only true if the channel bank is an upward rigid wall. The actual probability that a ship is grounded for a flooded channel, as illustrated in Figure 4, is given by [3]

$$P_g = P\left[Z \cup (Y \cap X)\right],\ \text{or } P_g = P(Z)+P(X)P(Y \mid X)-P(Z)P(X)P(Y \mid X) \tag{6}$$

where $P(Z)$ is the probability of ship grounding inside the channel border; $P(X)$ is the probability of ship excursion from the channel border; $P(Y)$ is the probability of ship grounding during the excursion, as discussed above, $P(X)=P(b,T)$; $P(Y|X)$ is the conditional probability of ship grounding during the excursion.

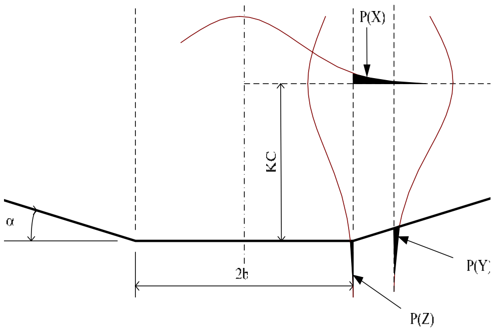

Figure 4: Grounding & excursion scenarios (black zones indicate probability of grounding)

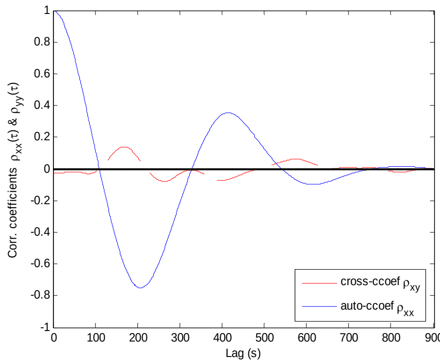

Figure 5: Cross- and auto- correlation coefficients

Consider a pair of the response ensemble $\{x(t)\}$ and $\{y(t)\}$ which respectively represent the horizontal and vertical motions of ship. It is perhaps not surprising that $\{x(t)\}$ and $\{y(t)\}$ are completely uncorrelated as shown in Figure 5, where $x(t)$ is a sample taken from the ensemble $\{x(t)\}$; $y(t)$ is a sample of the vertical motion obtained in the same environmental condition. Equation (6) can therefore be rewritten as

$$P_g = P(Z) + P(X)P(Y) - P(Z)P(X)P(Y) \tag{7}$$

Assume that the ship progresses with under-keel clearance KC (m); the channel has a type of flood bank with a slope angle α (degree) as shown in Figure 4. It is well-known that vertical motions of ship in waves can be considered as the Gaussian and ergodic random process with the mean value μ_y=0. So Equation (1) is applied to $\{y(t)\}$ as

$$v_h = \frac{1}{2\pi}\sqrt{\frac{m_{2y}}{m_{oy}}}\exp\left[-\frac{1}{2}\left(\frac{h}{m_{oy}}\right)^2\right], \text{ where } h = KC - \left[x(T_e) - b\right]tg\alpha \tag{8}$$

The term of $[x(T_e)-b]$ is considered as an exceeding distance (off-track) from the channel border during an excursion time period T_e (sec), which varies from time to time for each ship excursion. It should be realized that the further a ship moves away from the center of the channel, the longer a mariner will need to steer the ship back to a desired track. An effort [3] was made to investigate this phenomenon. In this case, we found that the probability density function of the time excursion fits well with the Weibull distribution as shown in Figure 6 for the case of half channel width b=100m.

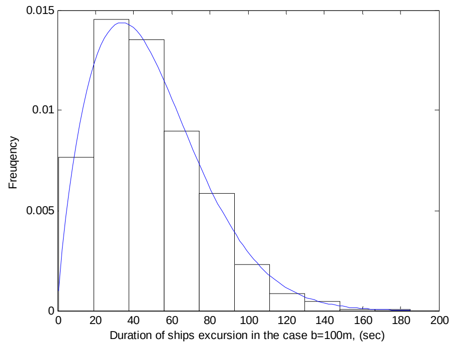

Figure 6: Probability density function of the time excursion fitted with the Weibull distribution

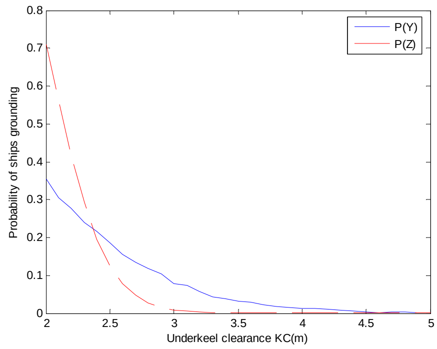

Figure 7: Probabilities of ship grounding for varying underkeel clearance KC

Monte Carlo simulation

Using the Monte Carlo method, the probability of ship grounding during excursion can be estimated by taking the following steps: 1- Generate a stochastic value of the time excursion as defined in Figure 6; 2- Determine the mean rate of crossing v_h as shown in Equation (8); 3- Determine $P(v_h,T)$ as defined similarly in Equation (1); Repeating the above procedure n times, the probability of ship grounding during a transit excursion can be estimated as

$$P(Y) = \sum_{i=1}^{n} P_i(\upsilon_h, T)/n \tag{9}$$

Numerical example

Continue the foregoing example by extending the condition that the spectrum of vertical motions of the ship at a critical point has been derived from the numerical model [7] in the same wave condition as mentioned above. The probabilities of ship grounding for different values of under-keel clearances KC for half channel width b=100m are plotted in Figure 7. It is interesting to observe that probabilities of ship grounding during excursion from the channel border, $P(Y)$, are even less than $P(Z)$ when values of under-keel clearances KC less than 2.3m. The curve of $P(Z)$ quickly drops with KC increases, while $P(Y)$ is more slowly reduced. Using Equation (7), finally, actual probabilities of ship grounding for the whole channel can be estimated with varying channel widths and under-keel clearances.

NON-STATIONARY PROCESS OF SHIP RESPONSE

The response ensemble $\{x(t)\}$ may be non-stationary in such a special case that meteorological and hydrodynamic conditions vary so frequently and considerably along the approach channel. However, it is highly likely that the response process $\{x(t)\}$ may become stationary when the mariner accustomed to such a condition. Much effort should be made to investigate this problem.

In this case the analysis procedures are almost the same as those of the stationary processes. The main distinction being that for non-stationary processes whose frequency content can be described in terms of time-dependent or evolutionary spectral density function $S(\omega,t)$. Time - dependent spectral moments, $m_i(t)$, can be obtained (by integrating $\omega^i S(\omega,t)$ over all frequencies) and used to determine the time - dependent mean crossing rate $\nu_b(t)$ [15,16]. The probability $P(b,T)$ in Equation (1) can be rewritten as

$$P(b,T) = 1 - \exp\left\{ -\int_0^T \nu_b(t)\mathrm{d}t \right\} \qquad (10)$$

The present approach has been extended to this problem, as will be reported in a future publication.

CONCLUSIONS

Since the whole channel can be designed in an integrated manner, an optimal design can be carried out by balancing channel depth and channel width; and total dredging volume will then be minimized for a specified acceptable risk of ship accident. Moreover, actual probability of ship grounding will be accurately estimated, which is the most important factor to establish safety criteria for the design and navigational operation of waterways.

The probability that a ship actually grounds during excursion from the channel limits, as indicated by $P(Y)$ in Figure 7, is totally different from the probability of ship excursion, as given by $P(X)$ in Figure 3. The difference is subject to the magnitude of under-keel clearance KC.

Before performing the fast Fourier transform, it is necessary to preprocess data by applying an appropriate "time window" to avoid "leakage" and "amplitude ambiguity" [1]. There are numerous such windows in current use; further investigation should be carried out to define an appropriate one.

As the number of observations increases, the normalized *rms* error decreases, but cost also increases proportionally. For practical application of this model, a balance between these factors should be found.

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